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TECHNICAL REPORT - SDC 641-2-15

HUMAN ENGINEERING STUDY OF THE AGSS569 CONTROL ROOM

Dunlap and Associates, Inc.
429 Atlantic Street
Stamford, Connecticut

SDC Human Engineering Project 20-F-2
Contract N8onr-641, T. O. II
Project Desingation NR-784-002

13 March 1952

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Dunlap and Associates, Inc.

FOREWORD

The Bureau of Ships requested human engineering assistance in the design of the control room of the AGSS569 submarine. This report describes the work done and contains recommendations made in reply to this request. Recommendations concerning the general layout of the control room, the nature of the controls, the design and lighting of the instrument displays, the general illumination of the control room and the seating arrangement for the operating personnel are presented and discussed.

The assistance of the Design Section of the Portsmouth Naval Shipyard, the Askania Regulator Company and Codes 515, 565G and 522 of the Bureau of Ships is gratefully acknowledged.

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Head, Equipment Applications Section

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~~SECURITY INFORMATION~~ [redacted]

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SUMMARY

PURPOSE

The purpose of this report is to present recommendations designed to improve the performance of operations within the control room of the AGSS569 submarine. Emphasis is placed on the layout of stations and equipment, the design of controls and instruments, the illumination of the displays, and correct seating for the operators.

PROCEDURE

The pertinent scientific literature was thoroughly reviewed including two previous reports of Dunlap and Associates, Inc., pertaining to the submarine control room. In addition to the review of the literature, activity analyses of operator performance aboard submarines were obtained, brief experimental studies were carried out under laboratory conditions, mock-ups and blueprints of the control room were inspected, and logical analytical evaluations were made.

RECOMMENDATIONS

This study has been directed toward a particular submarine. Although some of the findings and recommendations may be applicable to all present and future submarines, it must be remembered that, in general, they apply only to the AGSS569.

Because of the specific nature of the recommendations, they cannot be readily summarized. However, they have been placed at the beginning of each of the chapters for easy reference. Recommendations pertaining to layout will be found in Chapter II, page 5; controls, Chapter III, page 14; instruments, Chapter IV, page 29; illumination, Chapter V, page 47; and seating, Chapter VI, page 54.

CHAPTER I.

INTRODUCTION [1]

Background. The submarine of the future will be capable of traveling faster and at greater depths than present-day submarines. Consequently, controls and operating procedures now considered satisfactory may become intolerable if used with future submarines. As a prelude to the submarine of the future, the AGSS569 is being constructed. This submarine is to be an experimental one from which future submarines may evolve.

The design and performance of the AGSS569 will represent major departures from present submarines. One area in which there will be many changes is the control room. The removal of the conning tower will necessitate placing the periscope and helmsman's stations within the control room, thus limiting the amount of space available for the layout of work stations. Inclusion of the periscope area also presents problems of illumination particularly during night operations.

In order to improve the coordination of activities required to control the boat, a ship control station will be placed within the control room. At this station will be the two planesmen and the helmsman, and provisions will be made for three-man, two-man and one-man operation of the entire station. This innovation presents new problems in the design of controls and instruments. It also emphasizes the importance of proper seating as an aid to operator performance.

Purpose. The purpose of this report is to present recommendations designed to improve the performance of operations within the control room, particularly at the ship control station. As such, the report is concerned with five specific areas:

1. General arrangement of work stations within the control room (Chapter II).

[1] Appreciation is expressed to the following staff members: Messrs. O. Kahn, D. Huggins and J. Gibbons, and Misses J. Hund and L. De Michele.

2. Arrangement and design of controls at the ship control station (Chapter III).

3. Design and location of instruments for the ship control panel at the ship control station (Chapter IV).

4. Specific illumination requirements for the ship control and periscope stations and general illumination requirements for the room (Chapter V).

5. Design of seats for the ship control station (Chapter VI).

Methodology. A thorough survey of pertinent scientific literature was carried out. The research findings were organized and certain human engineering principles applicable to the problems at hand were extrapolated from these findings.

The results of two previous studies carried out by Dunlap and Associates, Inc., were used in those phases of this study concerning controls, instrumentation, and layout of work stations. The first study presented three proposals for the redesign of the diving control station; one of these proposals recommended that it face forward and be operated by a single man. The second study presented recommendations concerning the general arrangement of the manifold stations.

Attempts were made to obtain otherwise unavailable information by using the following methods:

1. Activity analyses of operator performance aboard submarines.

2. Brief experimental studies under laboratory conditions.

3. Inspection of mock-ups and blueprints.

4. Logical analytical evaluation.

Limitations of Study. This study has been directed solely toward the AGSS569. Some of the findings presented will be applicable to all submarines of the future and some will not. A second report is being prepared which will deal with the general problem of controls and instrumentation for all future submarines incorporating one-man control of the ship control station.

CHAPTER II.

LAYOUT

A. Recommendations

A schematic diagram of the proposed layout of the control room of the AGSS569 is presented in Figure 1. The proposed layout incorporates the following recommendations:

1. All equipment which is not operated by members of the diving control party should be separated from controls and displays essential for the vertical control of the boat. Such units as the Inter-Communications Switchboard, chart table, and all gyro equipment should be located in the starboard half of the control room as indicated in the schematic layout.

2. The ship control station should be located athwartships and adjacent to the port bulkhead. The location of the three operators should be from port to starboard as follows: the stern planesman, the bow planesman (or master controllerman), and the helmsman.

3. The diving officer should be located directly aft of the master controllerman's station. It appears advisable to give the diving officer an elevated rotating seat in order to facilitate his supervision of all activities in the control room.

4. The hydraulic manifold station should be located on the port bulkhead directly aft of the ship control station.

5. The trim manifold should be placed adjacent to and aft of the hydraulic manifold station.

6. If the inclusion of a remote control unit is anticipated for the trim and drain system, it should be located

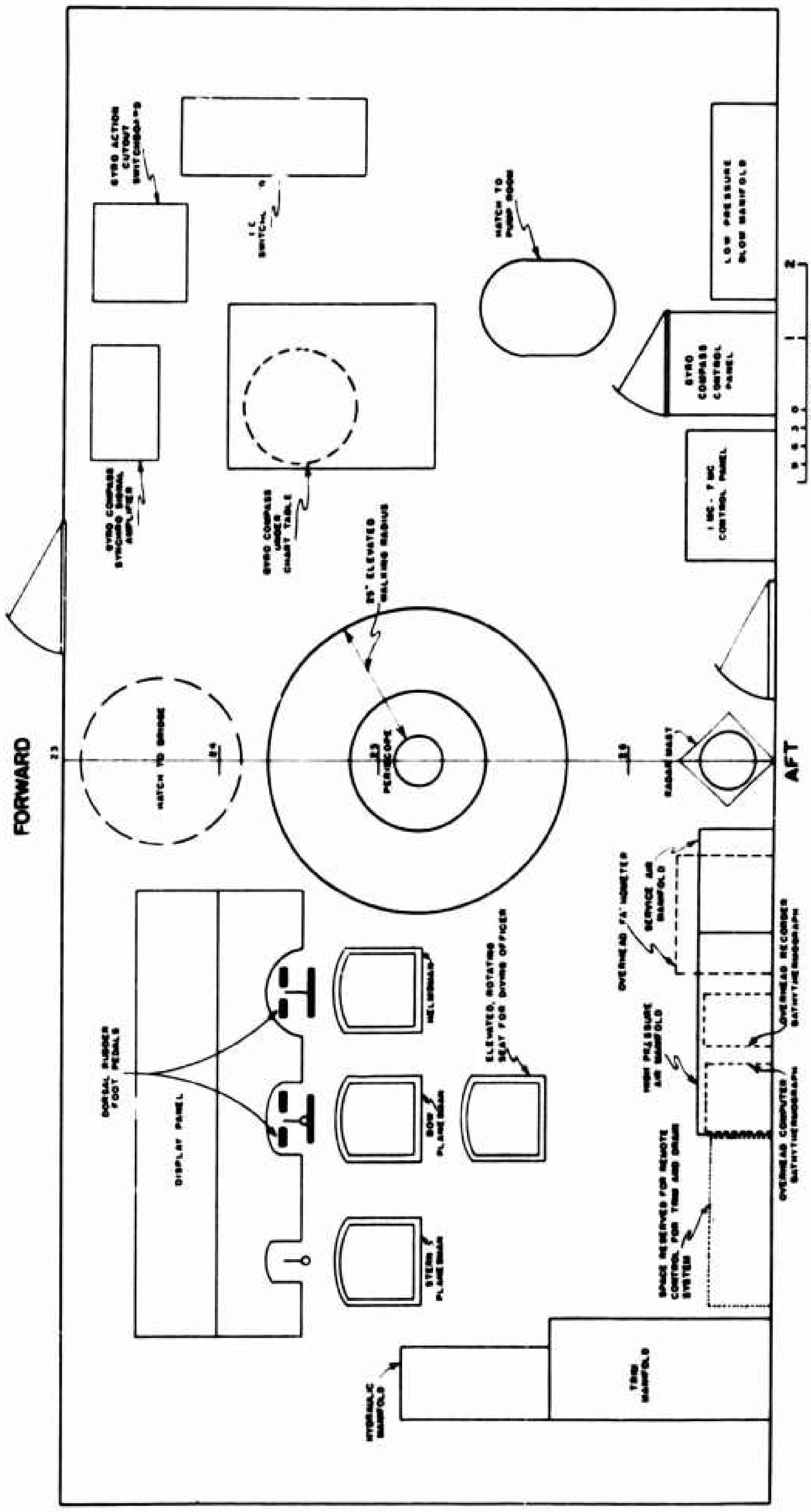

Figure 1. A proposed schematic layout of the AGSS569 control room stations and equipment.

on the after section of the control room perpendicular to the regular trim manifold station. Consideration should be given to one-man operation of both the trim and air manifold stations.

7 The high pressure air manifold and the service air manifold should be removed from their traditional positions on the starboard bulkhead and placed on the after section of the control room between the radar mast and the space reserved for remote control of the trim-drainage system.

8 The low pressure blow manifold station must be located near the starboard bulkhead due to piping and engineering limitations. No operational difficulties resulting from this location are envisioned since the station is manned only after the boat has surfaced.

9 The fathometer and bathythermograph should be located above the high pressure air controls and within direct view of the diving officer from his rotating seat.

B. Discussion

Aboard Fleet and Guppy type submarines, operation of the control room is hindered because functionally-related stations are not placed in positions which permit rapid and accurate communication of information among them. For example: two closely-allied units of equipment have been placed at opposite ends of the room, thus causing their operators to shout and use hand signals in order to coordinate their activities.

Aboard the AGSS569 the situation will be complicated further by the introduction of the periscope station into the control room, thus limiting the space available for other workplaces. Because the coordination of activities can be improved through the proper layout of workplaces, a study was made of the work stations in the control room, and the recommended placement of each is discussed individually in this section.

<u>Ship Control Station.</u> On present submarines the bow and stern planes are activated by large wheels located on the port bulkhead of the control room, and the rudder is activated by a steering wheel facing anthwartships in the conning tower. On the AGSS569 the helmsman (controlling the rudder) and the planesmen (controlling the planes) will work as a team under three-man operation. Under one-man operation a single operator will handle all three jobs. It is therefore essential that the three positions be placed together.

If the control station is placed on the port (or starboard) bulkhead, control of the rudder will become very confusing. As a compass placed on the bulkhead turns, the operator will find it difficult to determine the direction in which the boat is turning and the response he should make with his control in order to steer the boat properly. Placing the operators so that they face forward permits them to gain the proper orientation and to make "natural" responses with their controls. Therefore, it is recommended that the ship control station be placed athwartships.[1]

It is further recommended that the three operators of the ship control station be placed as follows:

1. The helmsman should be located nearest to the periscope area in order to receive orders directly from the Commanding Officer. This arrangement should alleviate much of the present communications problem wherein commands are frequently inaudible or misunderstood.

2. The master controllerman should be located in the middle in order that he may view all displays on the panel with a minimum of eye movement. During three-man operation this position should be occupied by the bow planesman. Chapter IV on instrumentation will substantiate the importance of this arrangement.

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1 WITH THE STATION IN THIS POSITION THE PLANES SHOULD BE CONTROLLED WITH STICKS MOVING FORE AND AFT AND THE RUDDER WITH A WHEEL. A COMPLETE DISCUSSION CONCERNING THESE CONTROLS IS PRESENTED IN CHAPTER III.

3. Because of the importance of the placement of the other two operators, the stern planesman should be located next to the port bulkhead.

<u>Diving Officer Station.</u> On current submarines the diving officer stands directly behind the planesmen and receives information from almost every part of the control room because of the wide distribution of the manifold stations. The distances separating the members of the diving control party and the high noise level result in an acute communications problem, many orders being inaudible and necessitating repetition.

During interviews with experienced diving officers, complaints were voiced concerning the crowded conditions surrounding the diving control stand; e. g., the ladder to the conning tower was continually in use during the crucial initial phases of each dive and the position of the ladder partially blocked the diving officer's view of the display panel.

In order to minimize the current communication difficulties and improve the flow of information to and from the diving officer, the following recommendations are offered:

1. The diving officer should be given an elevated rotating seat.

2. All manifold stations should be located near the diving officer.

3. The ladder to the bridge should be removed from the working area of the diving control party.

<u>Hydraulic Manifold Station.</u> At present, the location of the hydraulic manifold station is slightly forward of and adjacent to the diving control stand. Its isolation from the air manifold station precipitates a number of poorly-performed operations during "bleeding air," blowing the negative tank, etc. Much of this ineffective two-man operation and

the employment of hand signals necessitated by the high noise level in the room could be eliminated by a more concentrated arrangement of the manifold stations.

A modification of the remote control unit proposed for the SS563 has been recommended for the AGSS569. This remote control model has certain advantages over prior models inasmuch as it will occupy a smaller space, simplify operations and present controls and indicators in alignment. This unit should be located slightly aft of the ship control station.

Trim Manifold Station. Aboard current submarines the trim manifold station is located on the port bulkhead just aft of the diving control stand. At present, the air manifold operator must check the suction and venting of the trim pumps each time water is shifted, flooded or pumped into one or more of the variable ballast tanks. This additional check increases the number of verbal orders and reports passing among the diving officer, trim manifold operator and air manifold operator.

The proposed location of the trim manifold station in the AGSS569 control room should aid in solving the communication problem and in increasing the efficiency of operation. It has been suggested in a previous report (2) that placement of the trim manifold adjacent to the air manifold will allow one-man operation of the two stations. Combining the duties of these two operators would relieve the overcrowded conditions of the control room.

Remote Trim Manifold Station. An area adjacent to the trim manifold has been reserved for a proposed remote manifold for the trim and drainage system. Although the status of the construction of this unit is unknown at the present time, its proposed location in the control room appears satisfactory from an operational standpoint. If this innovation can be developed, it would be desirable for one man to operate both the air and trim manifolds. Activity analyses presented in a previous report (2) clearly demonstrate the desirability of this one-man operation in order to reduce the crowded conditions, to reduce the

number of verbal orders and reports, and to increase operational efficiency.

<u>High Pressure Air Manifold and Service Air Manifold Stations.</u>

On current submarines the air manifolds are located laterally along the starboard bulkhead of the control room. Their location places the operator at some distance from other members of the diving control party and precipitates the following operational difficulties:

1. "Bleeding air" is poorly performed because of the distance from the air manifold operator to the diving officer and the "Christmas Tree."

2. Checking of suction and venting of trim pumps must be performed each time water is shifted in one of the variable ballast tanks. This dual operation is both clumsy and time-consuming.

3. The blowing of the bow buoyancy and main ballast tanks is extremely awkward and noisy. During these operations, the commands from the diving officer are almost inaudible and sometimes require repetition before the orders are fully comprehended.

4. The blowing of the negative tank requires close integration of the operations of the hydraulic and air manifold operators. Since these stations are located on opposite bulkheads, the intervening distance makes efficient dual operation impossible. This fact has been supported by interviews with experienced operators who report that the negative tank is often blown either past the "mark" or not far enough. This discrepancy automatically affects the neutral trim of the boat and necessitates additional compensating actions by the planesmen.

Although many of these operational difficulties will be eliminated by the exclusion of certain tanks in the construction of the AGSS569,

communication between the manifold operators will still be ineffective. Therefore, it is strongly recommended that the high pressure manifold and service air manifold be located along the after bulkhead adjacent to the other diving control stations.

Low Pressure Air Manifold. At present the low pressure flapper valve controls are located along the after section of the starboard bulkhead. These controls are approximately 72 to 76 inches above the deck and, as a result, are extremely awkward to operate. Since the low pressure blowers are only activated after the boat has surfaced, no operational difficulties are envisioned by separating the low pressure manifold from the high pressure and service air stations. However, if the boat were forced to dive prior to the securing of the blowers, it might be necessary to have someone other than the air manifold operator take charge of the low blow manifold.

Because of engineering requirements and the limited space on the port side of the control room, it is recommended that the low pressure blow manifold remain in the starboard section of the control room. However, it is recommended that the flapper valves be lowered to within the normal reach of the operator.

Fathometer and Bathythermograph. At present the location of these instruments varies from boat to boat. The bathythermograph is usually placed somewhere above the chart table but within viewing distance of the diving officer. The fathometer, however, is generally located between the emergency helm station and the door leading to the officer's quarters--a location well beyond the viewing distance of the diving officer. Because of the placement of this instrument, the diving officer must request a fathometer reading from the chief of the watch. This procedure is highly undesirable since the chief of the watch must leave the hydraulic manifold station unmanned in order to obtain a fathometer reading. The introduction of an additional person to read the fathometer offers no solution since it will serve to aggravate the already overcrowded condition of the control room.

It is recommended, therefore, that both the fathometer and bathythermograph be placed directly above the high pressure and service air manifolds in order that they may be within easy viewing distance of the diving officer.

Auxiliary Equipment. On current submarines certain pieces of equipment seldom or never used by members of the diving control party are intermingled with the regularly or continuously functioning equipment. For example, the chart table, the gyro equipment and the radar equipment greatly impede operation of other equipment required for submerged runs. In addition, at all stations in the present control room, emergency and pre-set controls are indiscriminately placed with reference to the regularly used diving controls. This is especially true of the air manifold station. More efficient grouping of regularly used equipment should assure a higher level of performance, reduce the amount of required space, improve communications, and tend to prevent accidental activation of controls. It is recommended that all equipment not operated by members of the diving control party be separated from the controls and displays essential to the control of the boat. The Inter-Communications Switchboard, the chart table and the gyro equipment should be located in the starboard section and all diving control equipment should be located in the port section of the AGSS569 control room.

CHAPTER III.

CONTROLS

A. Recommendations

1. Controls should conform as closely as possible to the specifications appearing in Table I.

2. At a given speed, stick displacement should be proportional to plane forces and not to plane angle.

3. The stick should not be allowed to move freely or to lead the planes.

4. The planes should move at maximum speed when a force of two to three pounds is applied to the stick or four to six pounds to the yoke.

5. Simulated feel may be adopted as an alternative to recommendations 2, 3, and 4 above, provided it reflects actual control forces. It should reflect the effect of both speed and plane or rudder angle independently of the position of the control.

6. The helm wheel should not be allowed to move freely or to lead the rudder. However, since more error tolerance exists in the rudder control than in the plane control system, the helm wheel may move in proportion to rudder angle instead of to rudder forces.

7. The dorsal rudder foot pedals should be designed so that pressing the right foot pedal causes the boat to heel to the right and vice versa. This means that the right pedal should apply left dorsal rudder and the left pedal should apply right dorsal rudder.

8. The plane coupling ratio selector control should consist of a lever on the wheel of the master controllerman. It should be operable at all times irrespective of plane position.

Table I

Recommended control specifications

Design feature	Stick	SPECIFICATION Wheel*	SPECIFICATION Yoke	Pedals
Height from deck	29.0 in.	32.0 in.	35.0 in.	5.0 in.
Fore-aft range of movement**	15.0 in.		15.0 in.	
Length from pivot point	As long as possible		As long as possible	
Inclination at center of range	5 deg. forward of vertical		5 deg. forward of vertical	
Diameter		15.0 in.	15.0 in.	
Angular size of wheel		240 deg.	240 deg.	
Angle of wheel with deck		60 deg.	60 deg.	
Maximum wheel turn in either direction from center point		135 deg.	135 deg.	
Distance forward from back of seat +				28.5, 32.5 or 36.5 in.
Distance apart				18.0 in. ++
Movement required for maximum velocity of control surface movement +++	1.0 in.	1.0 in.	1.0 in.	
Force required for maximum velocity of control surface movement +++	2 to 3 lbs.	2 to 3 lbs.	2 to 3 lbs. (rudder) 4 to 6 lbs. (planes)	10.0 lbs.

* A LIGHT-WEIGHT WHEEL WITH FINGER GRIPS IS RECOMMENDED.

** THE STICK AND YOKE CONTROLS SHOULD BE CURVED OUTWARD AT SEAT HEIGHT OR THE FRONT OF THE SEAT WILL RESTRICT THE RANGE OF FORE-AFT MOVEMENT.

\+ THREE POSITIONS OF RUDDER PEDAL ARE DESIRABLE. THE EXACT DISTANCE USED WILL BE DEPENDENT UPON SEAT HEIGHT, DISTANCE FROM THE STICK, PEDAL TYPE, DISTANCE BETWEEN PEDALS AND RANGE OF PEDAL MOVEMENT. THESE FIGURES SEEM, ON THE BASIS OF AIRCRAFT LITERATURE, TO BE CORRECT FOR THE SEAT AND PEDALS RECOMMENDED BUT MAY REQUIRE SLIGHT MODIFICATION. THE PEDAL SHOULD BE SELF-CENTERING AT THE ZERO POSITION.

++ PEDALS SHOULD BE PLACED SYMMETRICALLY AS CLOSE TO THIS FIGURE AS POSSIBLE.

+++ IT SHOULD BE CLEAR TO THE OPERATOR FROM THE FEEL OF THE CONTROLS WHEN HE IS GETTING FULL PLANE AND RUDDER RATE, OR HE MAY TEND TO "FIGHT" THE CONTROL, ATTEMPTING TO GET A STILL FASTER RESPONSE. THE LOW FORCES RECOMMENDED, AND THE PROVISION OF A DISTINCT CUT-OFF POINT WHEN THE CONTROL HAS MOVED THE DISTANCE REQUIRED FOR MAXIMUM RATE SHOULD PROVIDE THIS. THE ARRANGEMENT RECOMMENDED RESULTS IN A CONTROL WHICH IS SELF-CENTERING AT THE EXISTING PLANE OR RUDDER ANGLE.

9 The plane coupling ratio selector should change the ratio of bow planes to stern planes by varying the ratio of yoke travel to stern plane travel without affecting bow plane travel. If possible, the adjustment should be continuous. A possible coupling selector design appears in Figure 2, p. 25.

10 Negative coupling ratios should be provided.

B. Discussion

The Problem of Submarine Control. As a submarine is propelled forward, horizontal control surfaces (planes) and vertical control surfaces (rudders) are moved in order to keep the boat on the desired horizontal and vertical courses. In general, tolerances are far smaller for vertical distance off course (depth error) than for horizontal distance off course (course error). As a result, the control of depth presents a more difficult problem than does the control of course.

Depth is maintained primarily by controlling the angle of the boat in the water. Boat angle is changed by turning the planes at either end of the boat, resulting in the application of a turning force or moment to the hull. Direction is controlled in analogous fashion through application of a horizontal turning force.

When one-man control is used, the problem of the operator can be summarized as follows: He is ordered to maintain a certain depth and direction; he must manipulate the planes and rudder in a manner which minimizes the difference between the actual and desired depth and direction. A good control system is one that allows him to do this efficiently.

The efficiency of a control system is difficult to assess. An efficient system is one in which errors in depth and direction accumulate slowly but can be corrected quickly. The relative emphasis on one or the other of these two requirements varies with the particular submarine situation. The system should be sufficiently flexible to allow accurate control (errors accumulating slowly) and quick application of

full control forces when quick changes are needed. The accuracy and rate of change characteristics of a control system can be established by changes in various design characteristics. However, the precise accuracy and rate of change characteristics required for this boat cannot be quantitatively ascertained from information now available. The proposed system, therefore, attempts to maximize both factors, at least with regard to depth control. This is effected through the design of the plane coupling ratio selector, which allows not only very sensitive depth control, but also quick application of full control forces when they are needed. The coupling ratio selector will be discussed fully elsewhere in this chapter.

Since one-man operation will be the most exacting control task (two-and three-man operation being only a division of the same control tasks among two or three men), the analysis presented here has been conducted primarily from the standpoint of one-man operation. The objective has been to provide a control system that will permit one man to control the submarine in the most difficult situations which can be predicted.

Methodology. The experimental literature that can be applied to this problem is exceedingly limited, indicating a great need for research in this area. It would be desirable to consider various designs for this control system, to analyze their advantages and disadvantages (including their engineering feasibility), and to select the most promising systems for experimentation. Then, by experimental comparison on a submarine simulator, the best alternatives could be selected. Unfortunately, arrangements for the experimental phase of this project could not be carried out. For this reason, alternatives have been selected on the basis of analytic considerations and the very meager data available. The final recommendations represent the best "educated guess" of individuals who have studied the control problem of this submarine carefully, using experimental findings whenever possible.

Limits to Recommendations. Many decisions relative to the control system were required at the outset of this study in order that work on the submarine might proceed. These have been decisions of expediency and

it may prove desirable to modify some or all of them on future submarines. They are as follows:

1. The system will be a submarine adaptation of aircraft-type controls.

2. The control stand will provide positions for three operators seated athwartships.

3. Under three-man operation, the left station will control the stern planes, the center station will control the bow planes, and the right station will control the rudder.

4. The center (bow planes) station will be able to take over the control of either or both of the other two stations.

5. Under three-man operation, the stern planes will be controlled by a stick moving forward and aft, the rudder by a wheel, and the bow planes by the fore-aft movement of a yoke (stick and wheel), all incorporating position control.

6. The planes can be coupled in varying ratios of bow plane angle to stern plane angle and both planes operated by fore-aft movement of the yoke.

7. Rudder control can be transferred from the right to the center station where it will be controlled by turning the wheel of the yoke.

8. The dorsal rudder, a control designed to give the operator control over the heel angle of the boat, will be operated by whoever operates the rudder. The controls will be duplicate foot pedals at the right and center stations.

9. The annunciator will be controlled by whoever operates the rudder.

These specific decisions determine the control stand to a great extent. The major remaining decisions that must be made relate to

control-control surface relationships, control-indicator relationships, plane coupling characteristics, resistance of controls (including frictional resistance and the possibility of simulated feel), and the exact specifications for the sizes, position and movement spans of the control. These problems are the primary concern of this chapter.

The recommendations for controls made in this chapter are based on the assumption that these controls will be used with the indicators and seats recommended elsewhere in this report. The control station is comprised of the controls, indicators and seats; they are so closely interrelated that a change in one affects all three. For this reason, deviations from the specifications for any of these should be considered carefully in terms of their effect on the entire control station.

Movement of Controls. Human engineering research indicates that certain movements of controls are "natural" or "expected" and lead to greater speed and accuracy of performance with less chance for reversal errors (17, 18). The stick, wheel and yoke conform in direction of movement to the population stereotype and to the controls on automobiles and aircraft. A clockwise movement of the wheel turns the ship to the right, while a forward movement of the stick tilts the bow down, and vice versa. The main problem in this regard comes in the construction of appropriate indicators, a subject discussed in Chapter IV.

A greater problem arises in the movement of the heel angle control. The dorsal rudder located just aft of the bridge will exert a force such that right rudder tilts the boat to the left and vice versa. This rudder is controlled by foot pedals. An experiment performed on 18 subjects showed that they all pushed the rising or "uphill" foot pedal to correct for a lateral tilting similar to the heeling of a boat. This means that the right foot pedal should apply left dorsal rudder, and the left should apply right dorsal rudder. The appropriate instruments of the panel should also conform to this orientation.

Plane Controls. Depth is controlled primarily through the application of forces to the boat by the planes. It seems desirable from the standpoint of the operator that the stick (or yoke) displacement should

bear a linear relationship to the plane forces. That is, moving the control a given distance should result in a constant change in the forces acting on the boat, regardless of the initial position of the control. If this condition is not met, the operator cannot determine kinesthetically the effect his movement of the control has on the plane forces.

In order to achieve this condition--even approximately--two major difficulties must be overcome. The first of these is the markedly non-linear relationship of the plane forces to the plane angles. For example: increasing the plane angle from 5 degrees to 10 degrees will result in a much greater increase in plane forces than that produced by increasing the plane angle from 20 degrees to 25 degrees. This non-linearity could be corrected by the use of a cam. This cam would cause the amount of plane movement for a given stick movement to become increasingly larger as the plane angle increases. In this way, a given change in the position of the stick will produce a constant change in plane forces throughout the entire range of stick movement.

An even more serious difficulty arises from the fact that the plane forces resulting from a given plane angle increase approximately with the square of the speed of the boat. If a constant relationship between stick movement and plane forces is to be maintained for all speeds, the total range of movement of the stick must be proportional to speed squared. This means that the range of the stick would have to be excessively long in order to accommodate the larger plane forces at high speeds. This would be both impractical and inefficient from the standpoint of construction and operation. An alternative method for achieving the same result (i. e., a constant change in plane forces for a given stick movement at all speeds) would be to limit the amount of plane forces available at high speeds to less than their full amount, thereby maintaining a reasonable range of stick movement. This method is the one utilized when the planes are coupled in accordance with the design proposed for the plane coupling ratio selector.

When the planes are not coupled (i. e., under three-man operation), the desired condition will not be obtained; the planesmen will be required to compensate for increased speed by reducing their control movements. It is reasoned that when the planes are operated individually, it will not overtax the planesmen to make the necessary compensation for speed; however, it might overburden the master controllerman to compensate for speed in addition to his other tasks.

Another basic problem in the design of the plane controls is whether to allow free movement of the control, or to restrict its movement so that it is a function of actual plane position. If a freely-moving stick is used, the planes will still move at a limited rate of speed and may take several seconds to reach the position ordered by the controls. Under this system, the operator has no means of determining the plane forces from the control position until he has held the control still long enough for the lag to be absorbed.

If the movement of the control is restricted so that it always corresponds to actual plane forces, the stick will always indicate to the operator both his actual plane forces and their rate of change. On the other hand, it might be misleading to provide the operator with a freely-moving control for a slow-moving control surface. Therefore, restricted movement of the control is recommended, with the additional stipulation that a slight control force cause the planes to move at their maximum rate, and that it be clear to the operator from the feel of the control when this maximum rate is attained. If this is not done, the operator may tend to "fight" the control to get a faster plane rate.

The control system used makes a difference in the design of the plane angle indicators. A freely-moving control is planned at the present time for the AGSS569 mainly because it will be easier to construct. Because of the difference between the system planned and the system recommended in this report, plane angle indicators appropriate to either system have been designed. The recommendations pertaining to these indicators appear in the chapter on instrumentation.

<u>Plane Coupling.</u> One-man operation requires that two sets of planes be operated by one man. This can be accomplished most effectively by coupling the planes together so that they may be operated by a single control. The manner in which the planes are coupled must take into account the following relevant facts:

1. For engineering reasons, planes will be coupled so that the ratio of their angles is constant rather than the ratio of their forces.

2. As speed is increased, the desirable ratio of bow planes to stern planes increases from 1:1 to some unspecified value. Ratios of at least 5:1 or 6:1 should be provided.

3. Different ratios may be appropriate under different conditions of operation, e.g., level flight will probably require a different ratio from diving or surfacing.

4. The operator should be able to change from one ratio to another quickly regardless of the existing angle of the planes.

5. Negative ratios of bow planes to stern planes should be available.[1]

Since several coupling ratios of bow planes to stern planes are required, a coupling ratio selector must be provided. This selector may be designed to operate in either of two ways: 1) the amount of bow plane angle corresponding to a given amount of stick movement increases as the ratio increases, or 2) the amount of stern plane angle corresponding to a given amount of stick movement decreases as the ratio increases. Either system would serve to increase the ratio of bow planes to stern planes.

The primary advantage of the first system is that full plane forces are always available with full stick movement; the second system, on the other hand, requires that the plane coupling control be set at a ratio of 1:1 in order for the operator to use full plane forces. However, the first system (increasing the amount of bow plane movement for a given stick movement) will have certain disadvantages--especially as pertains to over-controlling the boat. As the speed of the boat is increased from five or six knots to the maximum amount, the plane forces applied at a given plane angle are increased 15 to 25 times. Since higher ratios of bow planes to stern planes are desirable at higher speeds, the use of this results in a still greater application of bow plane forces per unit of stick movement.

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1 RESEARCH WORKERS AT THE TAYLOR MODEL BASIN HAVE REQUESTED THAT NEGATIVE COUPLING RATIOS BE AVAILABLE ON THE AGSS569. THE RANGE OF NEGATIVE RATICS REQUIRED IS NOT KNOWN.

The difference between the amount of forces applied per unit stick movement with the first proposed coupling system as compared to the second is approximately a function of the plane coupling ratio itself. In other words, with a 5:1 ratio, the first system applies five times as much force per unit of stick movement as the second. In view of the fact that plane forces increase so rapidly with speed, an additional increase due to the design of the coupling selector is highly undesirable and may present a serious problem of over-control at high speeds. For this reason, the second system, incorporating the coupling ratio selector which reduces the amount stern planes move per stick unit as the coupling ratio increases, is recommended.

From the standpoint of the human operator it is considered desirable to maintain an approximately constant relationship between the amount of stick movement and the effect of this movement on depth, irrespective of speed. Because plane forces at a given plane angle increase so greatly with speed, it is necessary that plane angle per unit stick movement be reduced at higher speeds. In order to avoid a separate control for this, a design for the plane coupling ratio selector is recommended which will simultaneously reduce control stick sensitivity and change coupling ratio. The ratio selector design that is suggested accomplishes this by allowing a progressive decrease of the amount of stern plane movement per unit stick movement. Finally, small amounts of negative stern planes can be used to counteract part of the large bow plane forces generated at very high speeds.

If the coupling ratio selector is used in this fashion, it will meet two needs. The first of these is to improve control by increasing the ratio of bow to stern planes. Experimentation has shown that at higher speeds, better control results by applying more bow planes than stern planes. This is a result of hydrodynamic rather than human factors in the control system, and would be as true of automatic as of manual systems. The second consideration is a result of purely human factors, the object being to keep the amount of plane forces per unit stick movement from increasing excessively with speed. The suggested coupling ratio selector appears to meet both these needs.

Negative coupling ratios can also be used effectively in maintaining very fine depth control. If sufficient counteractive stern planes are

applied to offset most of the bow plane forces, the boat angle will be only slightly affected by the total plane forces. However, the depth of the boat will be directly affected by the combined action of the planes since opposing angles on the two sets of planes result in an up or down force on the boat. A dive angle on the bow planes and a rise angle on the stern planes each produce a down force on the hull. The reverse condition results in an up force on the hull. The magnitude of these forces is very slight compared with the up or down forces involved when boat angle is changed. The result is a direct and fine control of depth which should prove advantageous for such operations as periscope runs.

Figure 2 illustrates the suggested design for the coupling selector control. The control is a simple lever designed to be mounted on the wheel of the master controllerman. The calibration in percent stern planes is such as to provide adjustment for all possible ratios of bow planes to stern planes greater than one (i. e., bow planes move as much or more than stern planes).

The "dead zone" marks the region in which stern and bow planes neutralize each other in their effect on boat angle. Complete neutralization of one set of planes by the other results in the loss of control over boat angle by the operator. The "dead zone" is, therefore, a danger area whose exact location must be computed by engineers.

The reverse zone is the area where the negative stern planes have more effect on boat angle than the bow planes. In this area therefore the control stick moves opposite the usual way, moving back for a dive angle and forward for a rise angle. The only reason for including the dead and reverse zones is that these negative ratios may be desirable for experimental reasons other than those discussed above. The type of experimentation desired by others who have requested negative ratios is not known by the authors, so the full range of possible ratios is included. Reverse zone ratios might prove useful for backing.

A "speed table" on the coupling ratio selector is suggested in order to indicate to the operator the correct coupling ratios for various boat speeds. This table should be calculated so that when the coupling ratio selector is set at boat speed it will maintain a constant relationship between plane forces and stick movement. Coupling ratios should be included on the indicator in the form of "Percent stern planes", since different ratios may be appropriate under

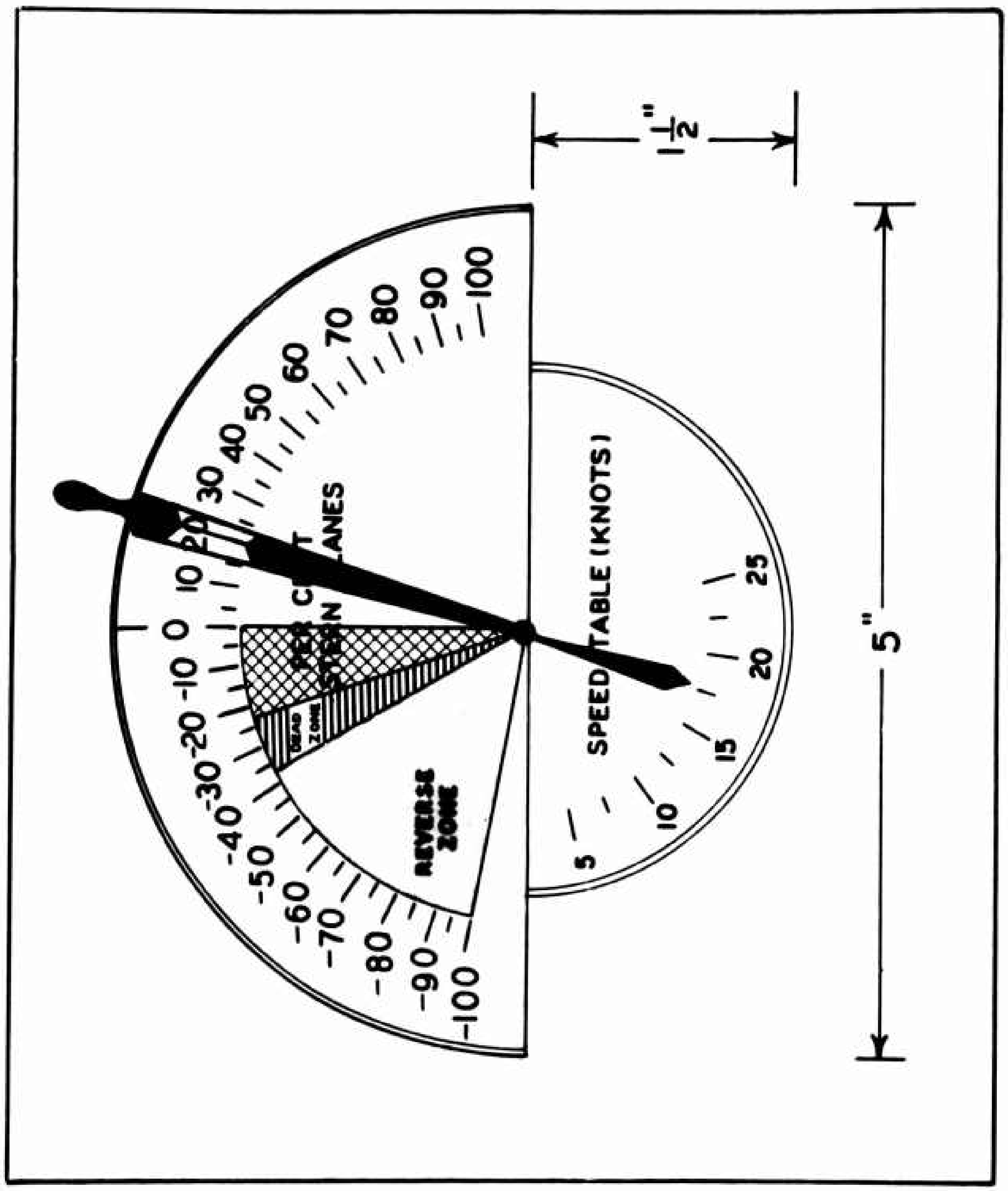

Figure 2. Proposed design for plane coupling ratio selector.

different conditions of operation (e.g., submerged level flight at a speed of 5 knots will probably require a different coupling ratio than diving at a speed of 5 knots). These coupling ratios may differ from the optimal ratios from a purely hydrodynamic standpoint, i.e., those ratios that would be best under automatic control. Nevertheless they probably represent the best solution for manual control.

Simulated Feel. Because of its effectiveness in aircraft controls, simulated feel has been under consideration for the aircraft-like controls of the AGSS569. However, there are many serious difficulties involved in adapting simulated feel to the submarine. Two of the most serious are as follows:

1. The control stick of the recommended system moves very slowly, moving with the planes. It is difficult to see how simulated feel could be adapted to this type of system.

2. With a freely-moving control stick, simulated feel should be a function of actual plane forces, and hence will lag behind the control stick position (ordered plane forces) just as the planes do. This is a difficult requirement to engineer. It means that regardless of stick position, feel may be exerted forward, backward, or not at all.

It was recommended earlier in this chapter that the control stick for this system be restricted so that it moves with the planes. Under this system, the position and movement of the stick provides the operator with the tactual information he requires regarding the plane forces in effect and their rate of change. It is felt that this system represents the most practical solution to the problem, and, therefore, it is the one recommended. Simulated feel, however, constitutes a possible alternative and may be used provided it can be made proportional to actual plane forces and not stick position.

Rudder Controls. The same problems of control design met in depth control occur in less severe form in direction control. In general, the control system adopted for the planes should also be adopted for the rudder

in order that the operator may perform similar operations to maneuver in both the horizontal and the vertical planes. If such an arrangement involves excessive engineering problems, however, more latitude can be taken with rudder controls than with plane controls. Although it is more desirable to have the helm wheel position correspond to rudder forces than to rudder angle, it is not critical that it do so. However, it is recommended that the movement of the helm wheel be restricted so that it is a function of rudder position. Under this system, the position and movement of the wheel will provide the operator with information concerning the rudder position and its rate of change. If the operator does not have this information, however, it will be less serious than the lack of the corresponding plane information, since he has a much greater error tolerance in operating the rudder.

Control Size and Movement Span. The specifications for controls which are presented in Table I, p. 15 were determined by a survey of the literature relating to aircraft controls (4, 6, 9, 12). A set of control specifications was prepared, and a mock-up of the control station, shown in Figure 3, was constructed on the basis of these specifications.[1] Some minor adjustments in control dimensions were made as a result of experimentation with the mock-up, and this revised set of specifications appears in the table. The actual size, position, and movement spans of controls were evaluated to some extent on the mock-up. Control force and movement specifications could not be evaluated and are included as they were originally derived, conforming when possible to values specified in research on aircraft controls.

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[1] IT WILL BE NOTED THAT ONLY ONE PAIR OF FOOT PEDALS APPEARS IN THE FIGURE. A DUPLICATE PAIR IS TO BE PROVIDED AT THE HELMSMAN'S STATION AT THE RIGHT OF THE PHOTOGRAPH.

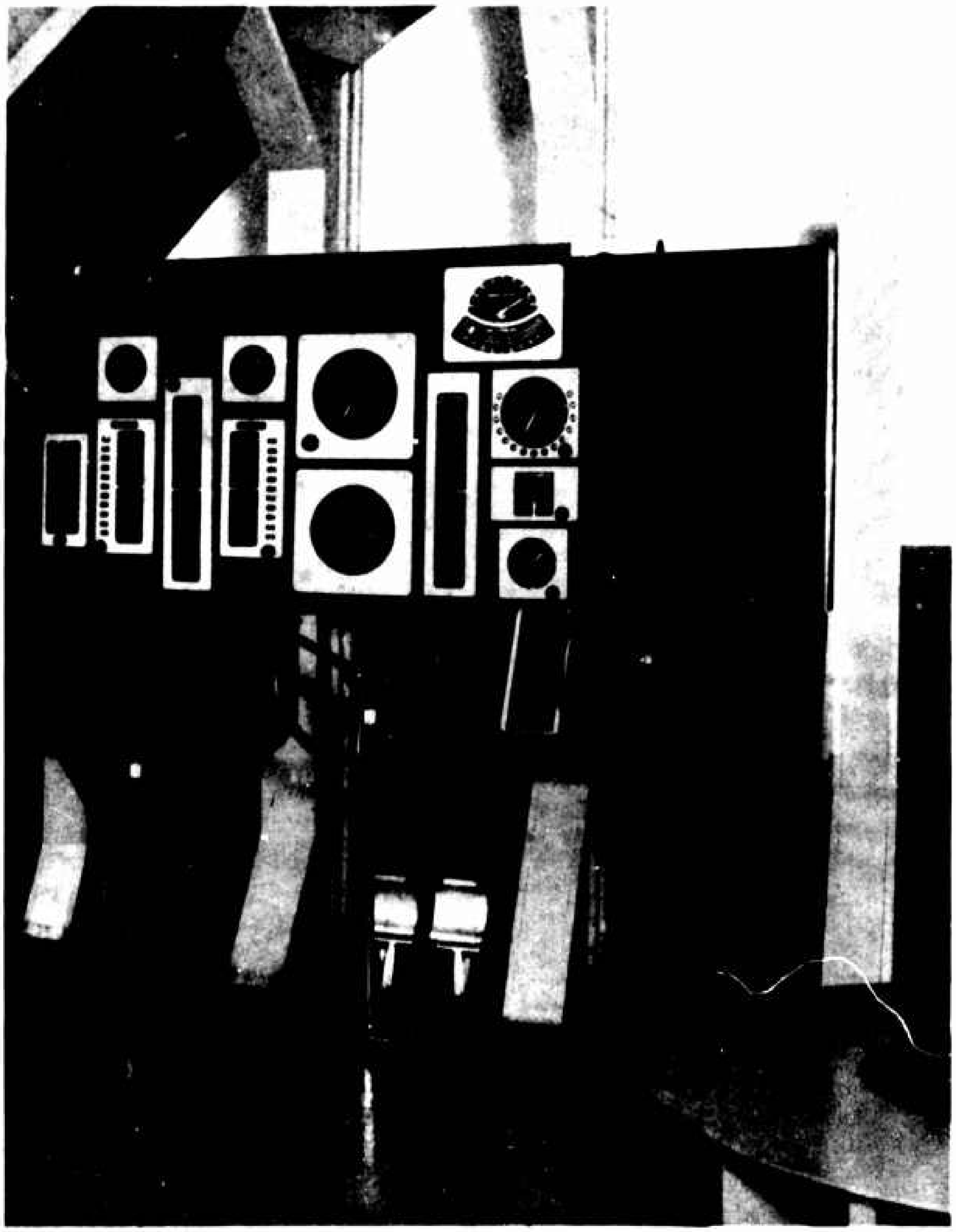

Figure 3. Proposed controls and instrument panel (Photograph of Askania mock-up dated 17 October 1951).

NOTE: A DUPLICATE PAIR OF FOOT PEDALS SHOULD ALSO BE SHOWN AT THE HELMSMAN'S STATION.

CHAPTER IV.

INSTRUMENTS

A. Recommendations

1. A recommended layout of instruments for the AGSS569 control panel is shown in Figure 4.[1] These displays are functionally arranged to accomodate one-, two-, or three-man operation of the stations and can be read easily and accurately by the diving officer from his position behind the ship control operators.

2. The recommended faces of these displays are presented in Figures 5 through 18 appearing with the individual discussions of each instrument.

3. Recommended dial specifications are shown in Table II. This table includes instrument nomenclature, dimensions of instrument faces, labels, height by stroke-width dimensions of numbers, height by stroke-width dimensions of letters, and length by stroke-width dimensions of scale graduations.

B. Discussion

General Arrangement. In order to design and arrange any group of instruments, it is first necessary to determine the type of information needed by each operator, the frequency of its use, the degree of accuracy required, and the over-all importance of the information to the operator.

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1 ALTHOUGH THE LAYOUT OF THE INSTRUMENTS ON THE SHIP CONTROL PANEL REMAINS THE SAME, THE FACES OF SOME OF THE INSTRUMENTS HAVE BEEN MODIFIED FROM THOSE SHOWN IN THE FIGURE.

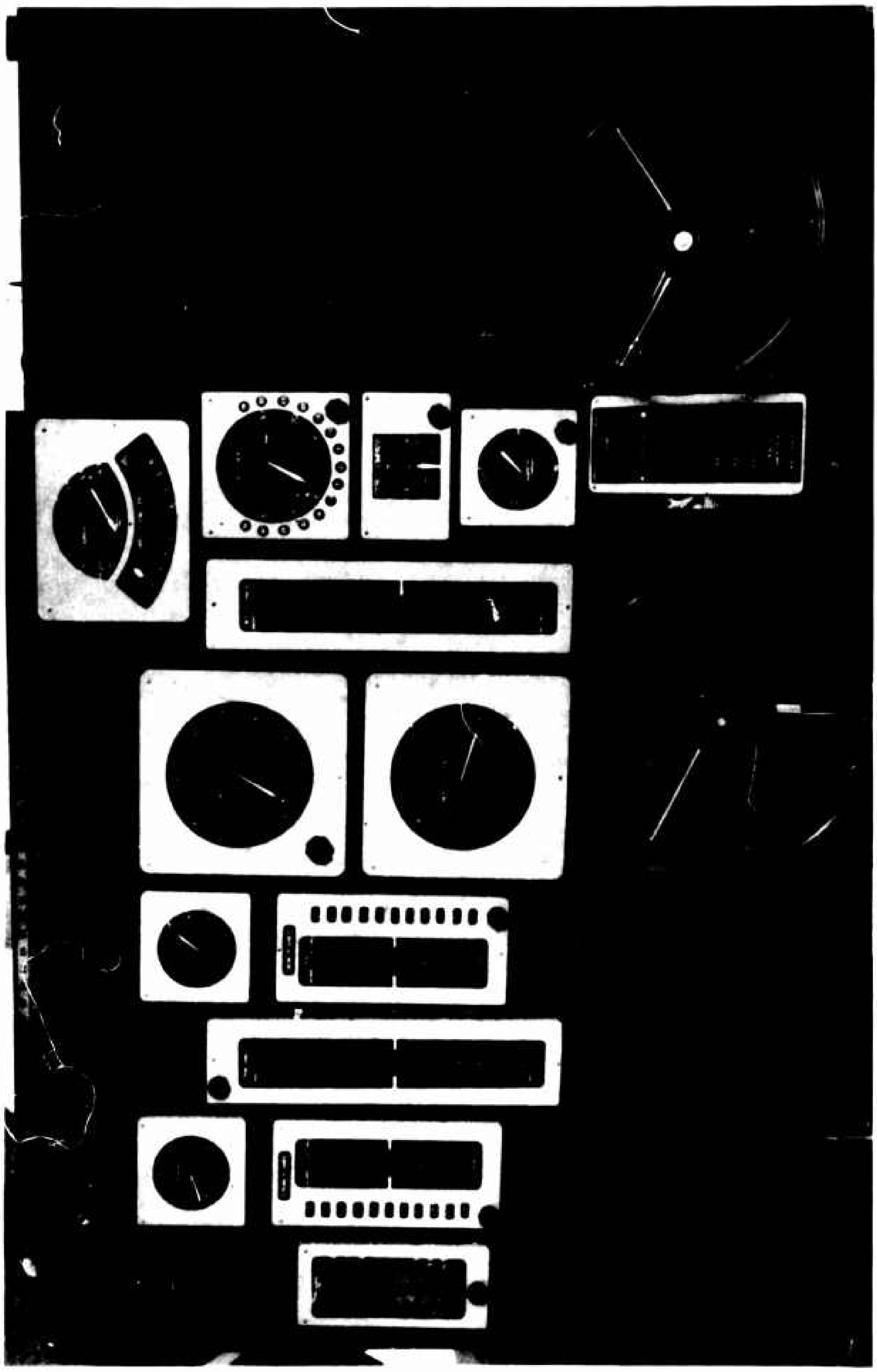

Figure 4. Photograph of Askania mock-up showing recommended location of instruments on the ship control panel. (The faces of certain displays have been subsequently changed; the revised instrument faces appear in the text. The right-hand side of the ship control panel has been reserved for an automatic steering console.)

Table II

Recommended dial specificati

	Dial title	Dial label	Dial shape	Case dimensions (Height by width)	Face size (Height by width or diameter)
1.	Auxiliary trim angle indicators	TRIM ANGLE	Rectangle	13 x 5	A. 0±45° Tube 10 x .70 B. 0± 5° Tube 7.5 x .70
2.	Hull pressure indicator	HULL PRESSURE	Circle	8 x 8	6
3.	Stern plane angle indicator	STERN	Rectangle	13 x 6.25	10.25 x 3
4.	Trim angle Indicator	TRIM ANGLE	Rectangle	20 x 5	17 x 3
5.	Speed indicator	KNOTS	Circle	6.25 x 6.25	4.5
6.	Bow plane angle indicators	BOW	Rectangle	13 x 6.25	10.25 x 3
7.	Auxiliary depth gage	DEPTH	Circle	11.5 x 11.5	8
8.	Primary depth gage	DEPTH	Circle	11.5 x 11.5	8
9.	Depth error Indicator	DEPTH ERROR	Rectangle	20 x 5	17 x 3
10.	A. Dorsal rudder B. Heel angle displays	A. DORSAL EFFECT and DORSAL ANGLE B. HEEL ANGLE	Semi-circle Arc segment	8.5 x 11	6 7.25 Cord length
11.	Rudder angle indicator	RUDDER	Circle	8 x 8	4.5
12.	Gyro compass repeater	GYRO COMPASS	Rectangle	5 x 8	3.5 x 3.25
13.	Magnetic compass repeater	MAGNETIC COMPASS	Circle	6 x 6	4.25
14.	Motor order telegraph (Annunciator)		Rectangle	12 x 5.5	11.5 x 4

* EXCEPT "DORSAL EFFECT" -.25 x .04

Table II

ti[illegible]ended dial specifications in inches

Case dimensions (Height by width)	Face size (Height by width or diameter)	Lettering (Height by stroke width)	Numbering (Height by stroke width)	Graduation markings (Length by stroke width)
13 x 5	A. 0±45° Tube 10 x .70 B. 0± 5° Tube 7.5 x .70	.18 x .03	.32 x .04	Tens - .38 x .04 Fives - .12 x .03 Units - .38 x .04
8 x 8	6	.18 x .03	.32 x .04	Units - .38 x .04 .5 Units - .25 x .03 .1 Units - .12 x .03
13 x 6.25	10.25 x 3	.18 x .03	Large - .32 x .04 Small - .24 x .03	Tens - .38 x .04 Fives - .25 x .03 Units - .12 x .03
20 x 5	17 x 3	.18 x .03	Large - .32 x .04 Small - .24 x .03	Tens - .38 x .04 Fives - .25 x .03 Units - .12 x .03
6.25 x 6.25	4.5	.18 x .03	.32 x .04	Fives - .38 x .04 Units - .25 x .03
13 x 6.25	10.25 x 3	.18 x .03	Large - .32 x .04 Small - .24 x .03	Tens - .38 x .04 Fives - .25 x .03 Units - .12 x .03
11.5 x 11.5	8	.18 x .03	.32 x .04	Hundreds - .38 x .04 Fifties - .25 x .03 Tens - .12 x .03
11.5 x 11.5	8	.18 x .03	.32 x .04	Tens - .38 x .04 Fives - .25 x .03 Units - .12 x .03
20 x 5	17 x 3	.18 x .03	Large - .32 x .04 Small - .24 x .03	Tens - .38 x .04 Fives - .25 x .03 Units - .12 x .03
8.5 x 11	6 7.25 Cord length	.18 x .03*	.32 x .04	Tens - .38 x .04 Fives - .25 x .03
8 x 8	4.5	.18 x .03	.32 x .04	Tens - .38 x .04 Fives - .25 x .03 Units - .12 x .03
5 x 8	3.5 x 3.25	.18 x .03	.32 x .04	Units - .25 x .03 .5 Units - .12 x .03
6 x 6	4.25	.18 x .03	.16 x .02	Tens - .25 x .03 Fives - .12 x .03
12 x 5.5	11.5 x 4	.25 x .04	.32 x .04	

5 x .04

[redacted] β

The proposed arrangement of the AGSS569 display panel is primarily based on operational measurements collected for a previous report (16) and additional data gathered during the course of this study. This research greatly aided in the functional location of each instrument. Data on the frequency and duration of eye fixations on various indicators by the bow planesman, stern planesman and helmsman were collected at the Askania Trainer at New London, Connecticut and aboard both Fleet and Guppy type submarines. An observer was stationed by the indicator panel where he could observe and measure the shifting of the operator's eyes from one indicator to another. An analysis of these data revealed the number of fixations per minute and the sequence of observations. A summary of the findings appears in Table III.

Table III

Fixation of instruments by diving control party during submerged operations

Indicator	Helmsman	Bow Planesman	Stern Planesman
	Fixation time - (percentage of total)		
Gyro Compass Repeater	68.9		
Rudder Angle Indicator	24.2		
Annunciator	3.9		
Depth Gage		59.4	4.5
Bow Plane Angle Indicator		31.3	
Trim Angle Indicator		4.7	71.7
Stern Plane Angle Indicator			18.7
Miscellaneous	3.0	4.6	5.1

Caution should be exercised in extrapolating from the data presented in this table since they are based on operational behavior involving a rate control system and a modified position control will be

adopted for the AGSS569 diving controls. However, the data are valuable in predicting information needed by the operators under three-man operation and have served as a guide for the general arrangement of the ship control instrument panel. Of course, if semi-automatic controlling is adopted, the plane angle indicators will probably be fixated nearly 100 percent of the time by the master controllerman or the planesmen.

General Principles of Instrument Design. Recently a number of experimental studies have been designed to determine the characteristics of scales, dial pointers, etc., which promote speed and accuracy in making readings. The principles stated here are extrapolated from numerous research studies and, in general, are incorporated in the recommended displays for the AGSS569 control panel. However, due to engineering limitations and the reading accuracy requirements of some displays, occasional compromises were effected which necessitated minor violations of the following principles.

1. Dials and instruments should be easily legible by all who are required to view them.

2. Visual displays should be centered near the eye level of the operator using them.

3. The indicators most important to each operator should be located in an optimal position; i.e., laterally close and at the horizontal line of sight.

4. Indicators should be located near their associated controls.

5. Functionally-related instruments should be placed adjacent to each other.

6. Indicators which are read in a definite sequence should be positioned to conform to this sequence.

7. Instruments should be designed to cover all possible conditions of operation.

8. Display panels should include all pertinent information. (Note: Laboratory experimentation is the best means of determining whether or not a particular instrument should be included on the panel. However, if such experimentation cannot be carried out, the instrument should be included.)

9. Dials and indicators should require a minimum of interpretation.

10. Indicator pointers should move in the same direction as their associated controls and, if possible, the control surfaces.

11. The position of zero on dials should be uniform; i.e., consistent null positions.

12. Irregularities in the sequence of numerals should be avoided.

13. All major scale markings should be numbered; intermediate markings should also be numbered when feasible.

14. Letters and numerals should be simple and unornamental in design.

15. The orientation of all fixed letters and numerals should be horizontal as opposed to radial or tangential.

16. Scales should begin and end with a numbered mark.

17. The number of units per scale division should be uniform and follow a decimal system as closely as practical.

18. Each display should be clearly labeled.

19. If critical markings are used to indicate maxima, minima, operating range and the like, such markings should:

    a. Be clearly visible.
    b. Remain distinct from the scale or numerals of the instrument.
    c. Be revised as modifications of the equipment occur.

20. If dual pointers are used within a single display, pointers should be designed so that the operator can easily differentiate one from the other; furthermore, each pointer should be clearly labeled.

21. Numerals, letters and scale divisions should have maximum visual contrast with their background; i.e., black figures on a white ground or white figures on a black ground.

22. Types of measurement should be simple and uniform.

23. Illumination should be adjustable for optimal legibility for all operational contingencies; glare should be avoided.

<u>Gyro Compass Repeater</u>. This display is of primary interest to the operator controlling the horizontal position of the boat. Because of its importance, the dial is located at the operator's horizontal line of vision, i.e., 46 inches above the surface of the deck. The display, however, must be placed midway between the helmsman's and master controllerman's positions so that either operator can view it easily.

It is recommended that this servo-operated instrument be a cyclometer with two continuous rotating drums. As the lower unit rotates ten numbers in one direction, the upper counter indicating tens and hundreds of degrees should advance one number. (See Figure 5.)

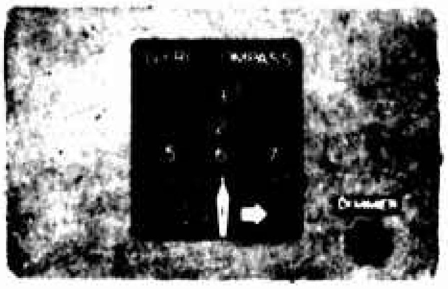

FIGURE 5. GYRO COMPASS REPEATER.

An auxiliary cue should be included to reinforce the proper control movement. Therefore, it is recommended that lighted arrows be placed on either side of the rotating drums so that when the wheel is turned in a counterclockwise direction, the left arrow will be illuminated giving the illusion that the fixed pointer is actually moving to the left. This recommendation should aid in eliminating reversal errors, i. e., turning the wheel in the wrong direction.

Since the level of illumination desired for the auxiliary cues may vary widely among the operators, it is recommended that a rheostat control be included on the casing of the instrument in order to permit adjustment of the illumination level.

Magnetic Compass Repeater.

This instrument, shown in Figure 6, serves as a stand-by or emergency gage for the Gyro Compass Repeater. Since the accuracy of the Magnetic Compass Repeater may be seriously questioned, it is recommended that it not be illuminated under normal conditions. However, a separate rheostat control should be included on the casing of the instrument in order that it may be illuminated when the gyro equipment is non-functional.

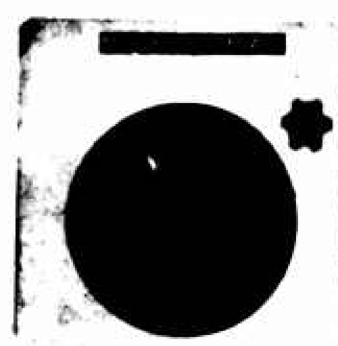

FIGURE 6. MAGNETIC COMPASS REPEATER.

Rudder Angle and Auxiliary Rudder Angle Indicators.

These two instruments are combined within one casing and are placed directly above the Gyro Compass Repeater since this display is closely associated with the former.

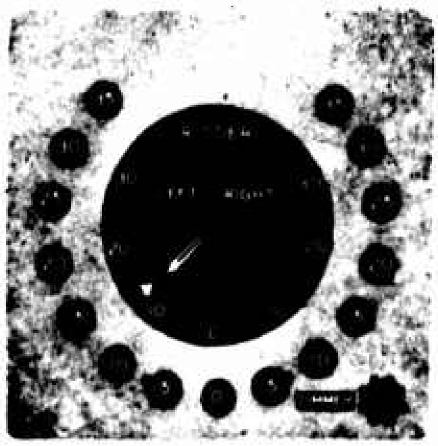

FIGURE 7. RUDDER ANGLE INDICATOR.

A dual pointer system could be employed; the longer inside pointer might indicate the actual position of the rudder and the outside pointer or "bug," the desired or ordered angle of the rudder. Whether or not the bug is appropriate depends on whether the helm wheel turns freely or is restricted in movement to correspond to the actual position of the control. These alternatives are discussed in Chapter III on controls.

The stand-by or auxiliary display is presented in the form of bead lights appearing every five degrees (See Figure 7). When the rudder is exactly midway between any two five-degree markings, both bead lights will be lit; as the rudder surface approaches one five-degree marker, the light further away will be extinguished, leaving only one light illuminated. In addition, a small reference line should always be illuminated so that the operator will be oriented with regard to whether he has put right or left rudder on the helm wheel. Illumination levels for the auxiliary bead light should be regulated by an individual rheostat control located on the casing of the displays.

Depth Indicators.

1. Primary Depth Gage

This important display should be placed directly in front of the bow planesman (or master controllerman) and below the auxiliary depth gage. It is a circular dial calibrated from zero to 100 feet with two counters: the upper counter to register actual depth in hundreds of feet and the lower one to indicate ordered depth (See Figure 8). A control knob for

FIGURE 8. PRIMARY DEPTH GAGE.

for setting the ordered depth should be placed on the dial casing within easy reach of the operator.

This gage will be of great importance to the controllers of the vertical plane of the boat during certain phases of diving and surfacing operations. However, when the boat is within 30 feet of the desired depth, the operator will probably shift his attention to the depth error indicator.

FIGURE 9. DEPTH ERROR INDICATOR.

2. Depth Error Indicator

This vertical display should indicate the difference between the actual depth of the boat and the ordered depth when the boat is within 30 feet of its ordered position. By presenting the information in this recommended display, mental interpretation will be minimized since the differential or subtraction factor is automatically computed for the operator (See Figure 9). This feature is based on a human engineering principle of minimizing the need for interpretation.

The information on this display will be perceived by the operator as an error corrector; e.g., if the boat is five feet below the ordered depth, the operator will put rise angles on the planes by pulling back on the control stick until the depth error pointer nears the null position. Thus, depth error information is presented in a manner which enables the operator to associate the direction of pointer movement with the movement of the control stick. Although it is felt that this instrument will become the prime depth indication when nearing desired depth and during level submarged flight, the trim angle indicator will probably be the most important display.

3. Rate of Depth Change Indicator

The inclusion of this display on the AGSS569 control panel is optional. If it is incorporated, the information should be presented

in a small circular gage reading in units of feet per second. A range lying between zero and 10 feet per second rise and dive should suffice for the more general or normally anticipated changes in ordered depth.

An instrument of this nature has already been installed on several currently operating submarines. The subjective reports from those diving officers who have had experience with this innovation are very favorable. In general, the reports state that the rate of depth change indicator has been helpful in maintaining proper trim of the boat. In addition, the display has served as a safety device to indicate whether the boat is diving too rapidly or too slowly.

At the present time, the diving officer estimates mentally the rate of dive from the movement of the depth gage pointer. The installation of the proposed gage might considerably minimize the need for such estimates.

Since the display is primarily of interest to the diving officer only, it is recommended that the indicator be placed well above the horizontal line of vision and parallel with the recommended locations for the hull pressure and speed indicators.

4. Auxiliary Depth Gage

This display, with a maximum range of 1,000 feet, will probably be used only in emergency situations. A standard Bourden tube type of activation should give acceptable accuracy. Since the dial will be needed infrequently by the operator, its proposed location should be above the operator's horizontal line of vision.

FIGURE 10. AUXILIARY DEPTH GAGE.

Trim Angle Indicator and Auxiliary Displays.

Trim angle information should be presented in a vertical form. As evidenced in experimental research by Vince (17), the movement of the pointer or any indicator should be closely associated with the movement of its control. Since the movement of the control stick is forward and aft, it logically follows that the output information should be presented in a vertical form with a down movement representing a forward control motion of the stick. Thus, a pointer indication above zero would be corrected by a forward movement of the control stick.

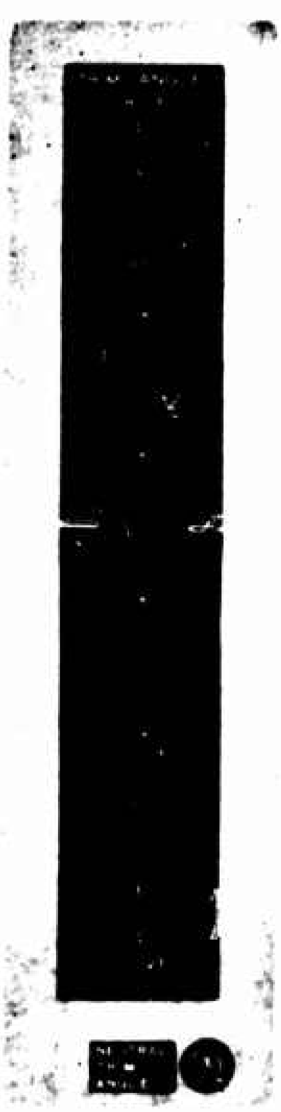

FIGURE 11. TRIM ANGLE INDICATORS.

This recommended display has two pointers of different shapes: one indicates the actual vertical angle of the boat and the other indicates the desired neutral trim angle. The latter pointer is pre-set by a control knob on the casing and indicates the trim angle that the boat should maintain during level flight. On present submarines the ordered neutral trim angle varies from boat to boat; but, in general, it lies between zero and two degrees dive. It is not anticipated that the trim angle control will be changed after the initial setting.

As shown in Figure 11, the distances between scale markings are geometric in nature; i.e., the distances between graduations representing five degrees around the null position are considerably wider than those at the extremities of the display. This type of scale was selected primarily because of the fact that small differences in trim angle become less important as the boat angle increases; while on the other hand, small angular changes are crucial between the range of five degrees rise and five degrees dive. Controllability of the boat angle is of primary importance when approaching and attacking a hostile craft; this operation must be performed at a neutral trim angle.

Although the planesmen will receive kinesthetic cues from the positioning of the control stick and from those experienced by actual boat angle, it is felt that the trim angle indicator will still remain the most important display on the ship control panel. Preliminary experimental data collected by Lts. Hollyer and Barry at M.I.T. on an electronic submarine simulator indicate that the trim angle indicator will be fixated a very large percentage of submerged operating time.

FIGURE 12. AUXILIARY TRIM ANGLE INDICATORS.

For auxiliary and stand-by indicators of trim angle, two additional vertical displays are recommended: a vernier with a range of plus or minus five degrees, and a more coarse display with a maximum range of 45 degrees dive and rise (See Figure 12). The two vertical columns may be filled with solutions of oil and mercury. Although the inertia of these displays will probably be somewhat greater than the present air inclinometer, the orientation will be correct. Since these stand-by displays are of secondary importance and used only under emergency conditions, a separate rheostat control for adjusting illumination levels should be included.

Hull Pressure Indicator. In designing a hull pressure gage, two contingencies must be met: 1) it must show the total range of pressure changes within the boat and 2) the diving officer must be able to detect a change of pressure as small as one-tenth of an inch. Since the diameter of this instrument is small and it is necessary to provide the widest possible spaces between scale graduations, the human engineering principle involving the covering of the numbers by the pointer has been violated.


FIGURE 13. HULL PRESSURE INDICATOR.

This instrument should have a range of 27 to 33 inches of barometric pressure. However, it is recommended that stops be eliminated at the maximum and minimum pointer positions to avoid rupture of the bellows diaphram if these values are exceeded. In order to emphasize the dangers of exceeding the maximum value or falling below the minimum pressure marking, the number at the bottom of this scale has been intentionally omitted. Since schnorkelling pparatus will not be incorporated in the AGSS569, the recommended limited range should cover all pressure changes.

The display should include two co-axial pointers distinguishably different in shape: one indicating actual hull pressure and the other to be used as a manually-set reference pointer (See Figure 13). The design of the proposed display should permit the diving officer to detect one-tenth of an inch pressure change when air is "bled" into the boat during the checking of water-tightness.

Speed Indicator. Although the maximum speed (or half-hour rate on the batteries) of the AGSS569 might possibly exceed 25 knots, a range from zero to 24 knots should meet all anticipated operational requirements (See Figure 14). The investigators recognize the fact that certain basic human engineering principles have been violated in the design of this instrument. However, since this display has already been constructed and is available for installation, it is felt that its use will not adversely affect performance. Although this display is of secondary importance to the operators of the ship control station, it materially aids the diving officer in correcting the trim of the boat.

FIGURE 14. SPEED INDICATOR.

Heel Angle Indicator. This indicator consists of a steel ball in a U-shaped glass tube. As presently envisaged, this display will be viewed only during high-speed submerged operations which necessitate large angles on the rudder. As the boat heels to port, the ball will appear to move

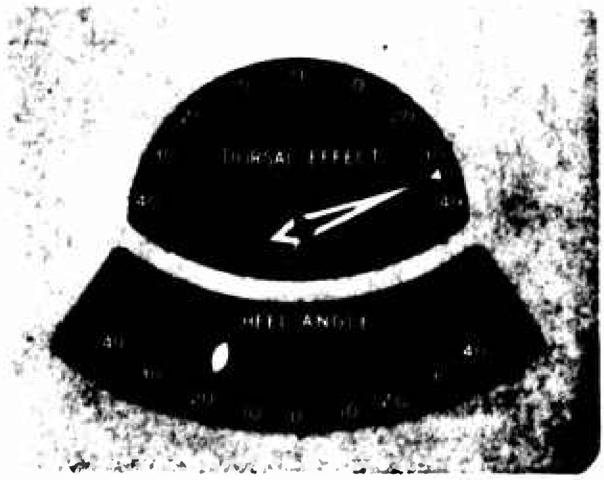

FIGURE 15. DORSAL RUDDER AND HEEL ANGLE INDICATORS.

in the same direction. In order for the operator to center the ball or remove the list angle, he must depress the right foot pedal. The reverse situation will occur when the boat heels to starboard.

As discussed in the previous chapter on controls, an experiment was performed in order to determine the pedal most naturally depressed to correct a list angle. All of the eighteen subjects tested pushed the "uphill" pedal, i.e., the one on the side of a table which was rising. The obvious disadvantage of this arrangement is that by activating the right foot pedal, the operator is actually applying left dorsal rudder. However, this problem should be greatly allevated by the recommended dorsal rudder and effect display which follows.

Dorsal Rudder and Effect Display. As shown in Figure 15, this display has one pointer, blackened in the center, which serves the dual purpose of indicating the actual dorsal rudder angle and the effect on the boat of activating the foot pedal controls. The upper portion of the pointer is emphasized since the operator will be primarily interested in the corrective action in effect to remove the heel angle by means of the foot pedals. Furthermore, an additional pointer or "bug" is included in the upper part of the display to indicate the desired position for correcting. This bug shows the operator the ordered position of the dorsal fin. In keeping with the emphasis on the effect portion of the display, it is recommended that the pointer indicating the actual position of the dorsal rudder be minimized since the operator will be less interested in the actual fin position than in the effect of correcting a heel or list angle.

Bow and Stern Plane Angle Indicators.

The presently-used plane angle indicators, now located on the port bulkhead, are unsatisfactory when placed athwartships because the direction of movement does not correspond with the movement of their associated controls. As previously mentioned, the most effective performance by an operator occurs when there is a "natural" or expected relationship between control movements and their associated indicators. When a fore-aft movement of the control stick is required, information can be interpreted most easily by the employment of vertical scales.

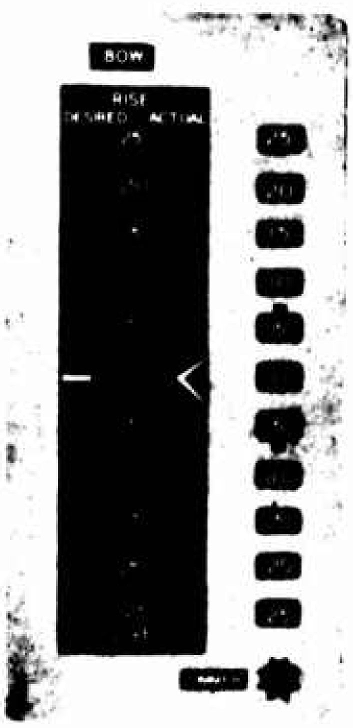

FIGURE 16. BOW PLANE ANGLE INDICATORS.

In Figures 16 and 17, plane angle indicators with dual pointers are shown. As presently planned, the control stick will move freely. For this reason, the position of the control stick will often not correspond with that of the planes which move very slowly. Under this system the pointer labeled "Actual" indicates the actual position of the planes; the second pointer, labeled "Desired," indicates the position of the stick. The position of the two pointers would be the same when the stick has been stationary long enough for the planes to catch up to it.

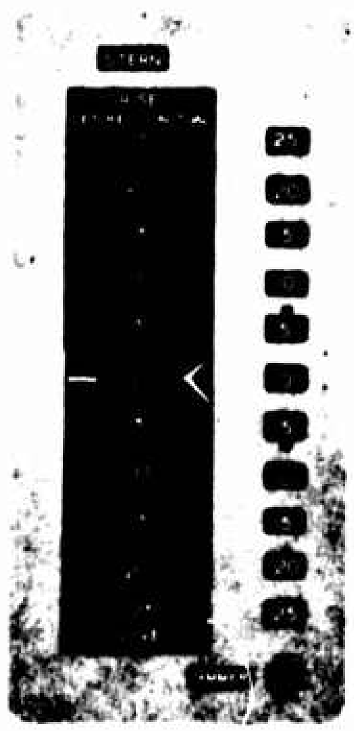

FIGURE 17. STERN PLANE ANGLE INDICATORS.

A different plane control arrangement has been recommended in the chapter on controls, in which the stick does not move freely but is restricted to correspond to the movement of the planes. With this system, there is no need for a second pointer under normal control.

Under two proposed systems of semiautomatic control, either the desired position of the planes is ascertained by a computer and is shown by the "Desired" pointer, or the computed plane angle error is shown by this pointer. In the first case, the operator will match the two pointers. In the second, he will act to reduce the plane angle error to zero. In either system, a second pointer is required.

Under the present rate control system, the plane angle indicators were viewed approximately 30 percent of the operating time and were observed by each operator about 20 times per minute, indicating brief check readings. With the adoption of position control the number of fixations should be considerably reduced because the operator will know the position of the planes from the position of his stick.

Auxiliary Bow and Stern Plane Angle Indicators. These emergency displays are incorporated on the casing of the normally operated plane angle indicators and appear as vertically-oriented bead lights at each five-degree interval (See Figures 16 and 17). Reference lines should appear at the null position and should be illuminated at all times for orientation purposes. Since these displays will seldom be read, rheostat controls for adjusting levels of illumination should be included on the casing.

Motor Order Telegraph (Annunciator). This instrument-control should be located on the lower panel projecting from the console at approximately a 60 degree angle. Its proposed location between the helmsman's and bow planesman's position should be optimal since either operator must be able to activate and/or observe the annunciator.

The controls consist of ten trans-illuminated lucite buttons for ordering various forward and backward speeds; an eleventh button is indicated for ordering connection of the batteries (See Figure 18). The recommended controls should considerably reduce the time required for activation, and it is felt that many current operational errors in ordering changes in speed will also be reduced. With the proposed instrument, the operator must merely push one button as opposed to

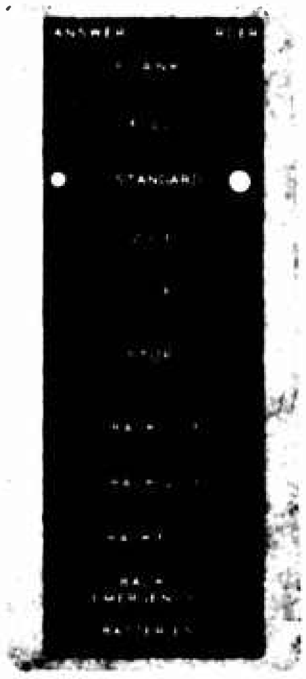

FIGURE 18. MOTOR ORDER TELEGRAPH (ANNUNCIATOR).

grasping a control knob and turning it between 10 and 200 degrees, as was required for all prior models. When a new speed is ordered by depressing a button, this button is automatically illuminated and the control ordering the prior speed raises and its light is extinguished.

On the opposite side of the display there should be a vertical line of bead lights indicating the acknowledgment of orders from the maneuvering room personnel. After a new speed is ordered by depression of the appropriate button by the helmsman, the Commanding Officer, diving officer, helmsman or master controllerman can observe the receipt of the order and the action taken to obtain the desired number of propeller turns.

The advantages of the proposed display control as opposed to prior models may be summarized as follows:

1. Greater color contrast is provided by the use of white-on-black to replace the formerly used light grey on dark grey.

2. A shorter time to activate controls is expected; a factor of appreciable importance under one-man operation which requires the operator to keep both hands on the control wheel much of the time.

3. There is better orientation of the display with reference to the position of the boat; i.e., the forward speeds are located on the forward tilted section of the lower console and the reverse speeds on the lower portion of the panel.

4. The proposed location of the display is within easy reach of the operators who may be required to use it.

CHAPTER V.

ILLUMINATION

A. Recommendations

1. Illumination of the control room should be such that: a) all visual tasks may be performed without strain during daylight operating conditions and b) dark adaptation conditions may be satisfied when they become necessary. Table IV presents specific lighting requirements.

2. A blackout curtain should be available for shielding the periscope area from the rest of the room in order that the Commanding Officer may maintain dark adaptation without lowering the illumination level of the rest of the room should he desire to do so.

3. Each instrument on the display panel should be trans-illuminated (internally illuminated) with red light during dark adaptation conditions in order to maximize brightness contrast, minimize the extraneous light reflected, and satisfy dark adaptation requirements.

4. During dark adaptation conditions a low level of red illumination should be used throughout the room in order to distinguish objects and to avoid the autokinetic or "floating" effect.

5. One master rheostat for all instruments and an individual screw driver adjustment for each instrument should be used to control illumination of all regularly used instruments. Individual rheostats should be provided for each auxiliary or pre-set instrument in order that they may be dimmed at the discretion of the operator. The maximum setting of all rheostats should be less than the brightness level which will destroy dark adaptation.

Table IV

General and instrument illumination in the control room of the AGSS569*

	Desired	Permissible From	Permissible To
Brightness ratios, bright and dark conditions			
Various dial markings within a given instrument	1: 1	1: 1	3: 1
Instrument to background	2: 1	1: 1	10: 1
Various instruments within a given panel	1: 1	1: 1	3: 1
Cathode ray tube to background	2: 1	1: 1	10: 1
Brightness ratio of instrument markings to background	100: 1	15: 1	400: 1
Lighting requirements for bright conditions			
Illumination on working areas	10 fc	1 fc	10 fc
Brightness of markings on instruments	10 ml	2 ml	20 ml
Brightness of indicator lights	50 ml	40 ml	100 ml
Brightness of cathode ray tubes	.10 ml	.10 ml	1.0 ml
Red lighting requirements for dark adapted conditions			
Brightness level for orientation	.001 ml**	-	-
Illumination on working areas	.02 fc	.01 fc	.03 fc
Brightness of markings on instruments	.10 ml **	-	-
Brightness of indicator lights	.08 ml	.04 ml	.10 ml
Brightness of cathode ray tubes	.10 ml	.10 ml	1.0 ml

* ADAPTED FROM ORLANSKY (11).

** THE MEDICAL RESEARCH LABORATORY OF THE NEW LONDON SUBMARINE BASE IS REPORTED TO RECOMMEND A BRIGHTNESS OF .10 MILLILAMBERT FOR SUBMARINE DIAL MARKINGS UNDER DARK ADAPTED CONDITIONS AND AN AMBIENT ILLUMINATION VALUE OF .001 MILLILAMBERT FOR ORIENTATION PURPOSES IN NON-WORKING AREAS.

6 All instrument marking, lettering and numbering should appear as white lucite on a black background. These colors will give excellent contrast during daylight operating conditions when they are illuminated externally and will be very effective when transilluminated during dark adaptation conditions.

B. Discussion

Maintenance of Dark Adaptation. During daylight operating conditions the illumination requirements of the control room are similar to those of any other area in the submarine: to provide ample external illumination so that all visual tasks may be performed without strain. However, the inclusion of the periscope in the control room results in illumination problems not present in other areas of the boat. During some night operations the Commanding Officer may need to use his periscope in order to obtain certain information. Under overcast conditions with little light coming from the moon and stars, the Commanding Officer is able to view targets through his periscope only when he is dark adapted. In order for him to become and remain dark adapted, he must not view any brightly-lighted display. Any sacrifice in his adaptation level means a decreased chance of sighting a target. The times required to adjust to certain brightness levels after exposure to light are shown in Table V, taken from reports of the Medical Research Laboratory, New London, Connecticut (7, 8).

Table V presents excellent reasons why the Commanding Officer should avoid looking at brightly illuminated display panels, light fixtures, etc., during night operations. Further evidence is presented by Sperling and Farnsworth who found that after viewing a radar scope, a long recovery time was required to view targets illuminated as high as full moonlight (15). Fixation on the "Christmas Tree" and red-illuminated dials produced smaller but still appreciable decrements.

On the basis of this information, it is recommended that an adjustable blackout curtain be provided at the periscope area. If he desires to do so, the Commanding Officer may lower this curtain and remain inside it, thus preserving his own dark adaptation without interfering

with the general illumination of the room. If he does not desire to use the curtain, the entire control room must be lighted by a very low level of red illumination. (See Table IV, p. 48).

Table V

Dark adaptation times (Times given in minutes and seconds, e.g., 0: 0).

Initial brightness level (in foot-lamberts)	Final brightness level (in millilamberts)			
	Full moon .01	Half moon .001	Clear starlight .0001	Overcast starlight .00001
	Dark adaptation time			
140 white light	0: 12	4: 36	8: 24	16: 34
6* white light	0: 1	0: 11	2: 24	8: 33

* THIS BRIGHTNESS LEVEL APPROXIMATES THAT CURRENTLY FOUND ON SUBMARINES.

Internal and External Illumination. The lighting of instruments from the rear provides good legibility at low levels of illumination. A study by Berger in which it is shown that slender, internally-illuminated numerals are 18 percent more recognizable at the 10-watt intensity than white numerals of optimal stroke-width with optimal external illumination (1). It is recommended, therefore, that all instruments be illuminated from the rear.

During night operations, the use of internal illumination with no external lighting creates visual illusions in the form of autokinetic movement; i.e., the high contrast between the figures and their background gives the operator the illusion that the figures move or "float." Many studies have been carried out proving the existence and influence

of this optical illusion. The degree of autokinetic illusion created by a single sphere of light varies considerably from person to person as demonstrated in a study by Sherif (14).

In order to avoid this "floating" movement caused by the absence of external illumination, it is strongly recommended that during night operations a very low level of external illumination supplement the higher internal illumination of the ship control displays.

Red Illumination. All available experimental evidence points to the superiority of red illumination over any other type when the maintenance of dark adaptation is necessary. Because the rods of the retina are relatively insensitive to red light, its use allows a maximum degree of dark adaptation.

In a summary report of the existing literature on this visual problem, Luckiesh and Taylor state that an operator can gain a certain dark adaptation level more quickly while working in an area of dim red light than in one illuminated by white light of an equal intensity (5). Furthermore, the same investigators demonstrated the superiority of red light over white light at low intensity levels for reading ordinary printed matter, maps, charts, and instrument dial markings. Experiments carried out by Seitz and Orlansky confirmed the superiority of red illumination (13). After adapting subjects to a light intensity of 0.725 millilambert (approximating the internal illumination level of an airplane cockpit), the investigators attempted to determine how rapidly a subject could see an object in the dark (instantaneous threshold). Both white and red adapting lighting of 0.725 millilambert intensity were used. The data collected on five subjects indicated that without exception the instantaneous threshold was lower following exposure to red adapting light than following exposure to white light of the same intensity. Further analysis of the data revealed that an individual's sensitivity for fixating a dim object such as that encountered in the night would be about four times greater after viewing a panel illuminated with red light as opposed to white light. The above findings have direct application in spotting targets at night through the periscope. It is recommended, therefore, that red light of an

appropriate wave length be used for internal illumination of the instruments during night operations when dark adaptation must be maintained. External illumination of the room during these periods should be effected by red light of a low level of intensity.

Rheostats. The proposed lighting system of the display panel should be equipped with some means of adjustment in order that the operators may have a range of light intensities available. It is recommended that knob-controlled rheostats be used for this purpose. Since all of the regularly used instruments will probably require the same amount of illumination, one master rheostat should be provided for these instruments. On the other hand, it is quite likely that only one or two of the auxiliary instruments will be used at any one time in place of non-functioning regular instruments. Therefore, it is recommended that each of the auxiliary or stand-by instruments be provided with a rheostat in order that one may be illuminated in an emergency without illuminating the others. This arrangement will also permit the operator to reduce the amount of illumination emitted from the auxiliary instruments in order to emphasize the light from the operationally needed displays. Each of the regularly-used instruments should have individual screw driver adjustability of illumination located behind the display casing. The construction of all displays should be such that dead light bulbs can be easily and quickly replaced.

It is recommended that the maximum setting for all rheostat controls be less than an illumination value which might materially damage dark adaptation conditions. (See Table IV for specific illumination values.)

Color Contrast. A special problem exists in many instrument reading situations where dark adaptation conditions must be maintained. In order to protect dark adaptation: a) the illumination should be dim red and b) the area of the visual field emitting or reflecting light should be minimized. In terms of instrument design, this necessitates an arrangement of bright figures on a dark background. During periods of dark adaptation, the bright figures should appear "red" on a black

background. When dark adaptation is not maintained, the same instruments appear as white on a black background. Black-on-white might be a more desirable arrangement for bright conditions, but the adverse effects, if any, of white-on-black will be slight. For these reasons, white-on-black is the recommended color contrast for the numerals, letters, pointers and scale markings of the ship control panel.

CHAPTER VI.

SEATING

A. Recommendations

1. The seats used for the diving control station should conform to the specifications of Table VI and Figure 19.

2. If custom-made seats are not constructed for the diving control station, standard seats (such as aircraft pilot seats) conforming as closely as possible to the specifications listed should be obtained.

B. Discussion

It was stated in Chapter III that the controls, instruments and seats of the diving control party are so interrelated that a change in one may well occasion changes in the others. Thus, the foregoing seating recommendations presuppose the use of the recommended controls and instruments, at least in all major respects.

Seating is an aspect of the diving control station that has been seriously neglected in the past. The planesmen's seats on current submarines are so poorly designed that the operators are unable to sit on them and generally operate from a standing position with one knee on the seat (15). The exact degree to which this situation hampers the planesmen's performance cannot be definitely stated. It is obvious, however, that the position the planesman must take because of the seat is awkward, fatiguing, and inefficient. In view of the precision which will be required in the operation of the AGSS569, it is important that the operators be provided with seats designed to improve their performance and to contribute to their comfort. For this reason, the seating problem has been carefully analyzed.

In approaching this problem, the investigators recognized that the design of a seat for a particular work station should be based upon consideration of three basic factors:

Table VI

Recommended seating specifications*

Design feature	Specification
Horizontal line of vision from deck	46 in.
Seat reference point to eye (average)	31 3/4 in.
Height of reference point (average)	14 1/4 in.
Seat adjustment, vertical	±3 1/2 in.
Seat adjustment, horizontal	±1 1/2 in.
Seat back angle, from vertical	16 deg.
Seat angle, from horizontal	5 deg.
Angle, seat back to seat	101 deg.
Seat width	15 in.
Seat length	15 in.
Width of back (tapering from top to reference)	17 in. to 15 in.
Height of back	23 in.
Height of arm rests from seat	9 1/4 in.
Cushioning	Foam rubber or fiber-glass bat

* THE CONTOURS OF THE BACK REST AND SEAT CUSHION SHOULD BE SHAPED TO CONTACT A LARGE AREA OF THE BODY.

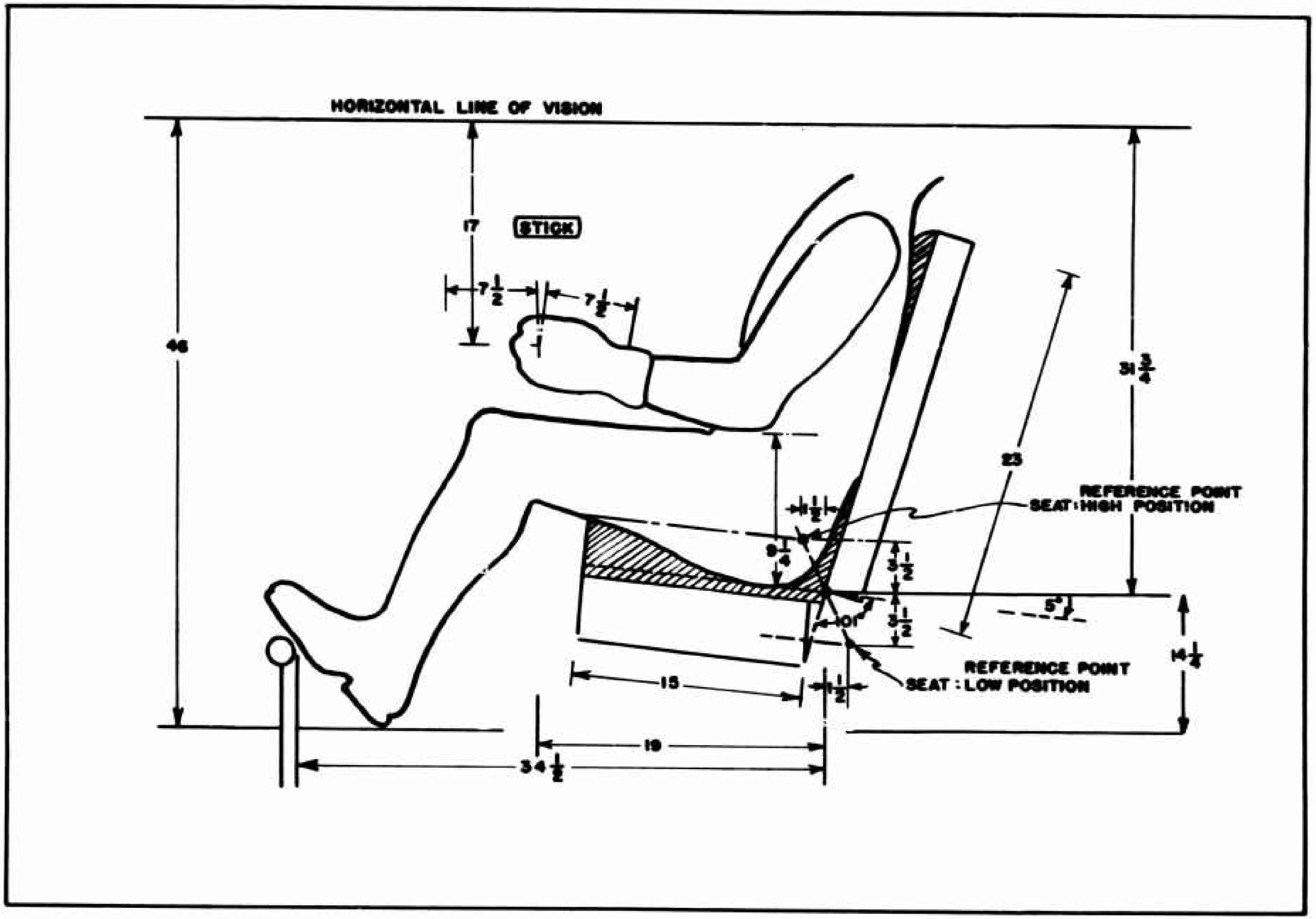

Figure 19. Seat for the diving control stand of the AGSS569. (Adapted from Randall (12)).

1. The function, design and arrangement of controls, instruments and equipment to be used.
2. General principles of seat design.
3. Physical dimensions of the operators.

Recommendations with regard to the design and arrangement of controls and instruments have been discussed in preceding chapters of this report. General principles of seat design and physical dimensions of the operators will be treated in the following discussion.

<u>Principles of Seat Design.</u> The following general principles were applied in developing specifications for the proposed seat (3).

1 The contours of the back rest and seat cushion should be shaped to contact a large area of the body.

2 The back rest and seat cushion should be lined with cushioning to minimize pressure on small areas of the body. (Foam rubber or fiber-glass bat make acceptable cushioning.) Particular attention should be paid to three pressure areas:

a. The thigh region at the front of the seat.
b. The lumbar region or small of the back.
c. The shoulder-blade area.

3 The range over which adjustment can be made should conform to the body builds of all, or nearly all, the population using the seat.

4 All conditions of operation should be considered in designing the seats.

Since the recommended controls represent an adaptation of aircraft controls, it is logical that the seat appropriate to these controls should be an adaptation of an aircraft seat. Specifications for a particular aircraft seat were selected on the basis of the above general

principles. Slight modifications were made in these specifications to conform with the requirements of the submarine situation.

Physical Dimensions of Submarine Operators. In order to design correct seats for use by submariners, various physical dimensions of the submariners should be known. Complete anthropometric data on submariners are not available. However, such data are available on fliers and other military personnel. Table VII presents the measurements gathered from a group of aviation cadets.

The data presented in Table VII can only be used if the physical dimensions of submariners correspond with those of aviation cadets. In order to determine whether this is a safe assumption to make, height and weight measurements of a group of submariners have been obtained from the Medical Research Laboratory at New London, Connecticut. Preliminary findings indicate that the two groups do not differ significantly, and that, therefore, the anthropometric data obtained from aviation cadets may be used in designing equipment for submariners.[1]

Results. The seat specifications presented in Table VI and Figure 19 at the beginning of this chapter correspond closely to those recommended for aircraft seating by Randall (12). However, it would be desirable to construct an experimental model of the seat for evaluation before actual installation of the seat in the control room.

A wooden model of the seat was built in connection with the mock-up of the diving control stand. This seat embodied the over-all dimensions for seat height, width, etc., but none of the adjustments in these. As a result of tests of the model seat, some changes were made in the recommended values for over-all seat size. These modified specifications are the ones appearing in the table.

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[1] A DETAILED DESCRIPTION OF THESE FINDINGS WILL BE PRESENTED IN A LATER REPORT.

Table VII

Anthropometric data related to seat design

Part of body	Mean (in.)	Standard deviation (in.)	Range** (in.)	Seat reference
Sitting height	36.4	1.3	33.8 - 39.0	Mean position of reference point
Elbow-seat *	9.6	0.6	8.4 - 10.8	Back cushion design
Shoulder-elbow	14.7	0.7	13.3 - 16.1	Stick position
Forearm length	19.5	-	19.5	Stick position
Seat length*	18.9	1.0	16.9 - 20.9	Seat length
Seat height	19.0	0.9	17.2 - 20.8	Reference point height
Patella height	22.0	1.0	20.0 - 24.0	Foot pedal position
Foot length	10.5	0.4	9.7 - 11.3	Foot pedal height
Bi-trochanteric	14.0	0.5	13.0 - 15.0	Seat width
Bi-deltoid	18.0	0.7	16.6 - 19.4	Back width

* THESE MEASUREMENTS ARE FROM A SAMPLE OF 1959 CIVILIANS FROM 17 TO 89 YEARS OF AGE; ALL OTHER MEASUREMENTS ARE FROM A SAMPLE OF 2950 AVIATION CADETS (19).

** INCLUDES ALL BUT 4.6 PERCENT OF THE POPULATION (MEAN ±2 STANDARD DEVIATIONS).

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